New Approaches for Atmospheric Turbulence-Degraded Image Correction

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Discussion Topics

Isoplanatic and Anisoplanatic Imaging Through Turbulent Me

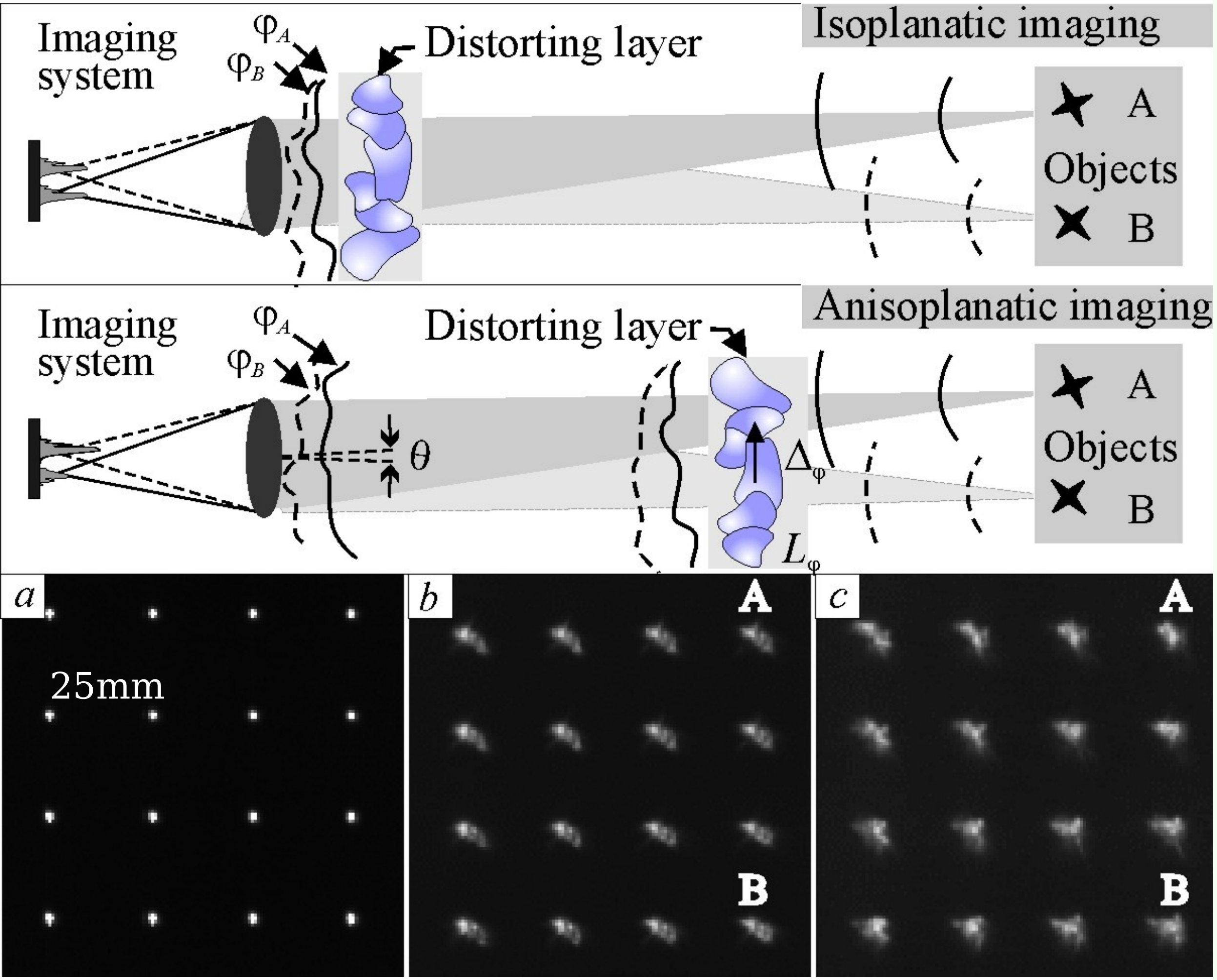
- **Image Quality Analysis: Edge-Metrics**
- **“Lucky-Frame” Selection**
- **Adaptive Optic Compensation**

Image Fusion (synthetic imaging) Technique

- **Local Image Quality Analysis: Image Quality Map**
- **Image Fusion Based on PDE Process**
- **Atmospheric Experiments**
- **Turbulence-Induced Image Quality Enhancement**

Anisoplanatic Imaging Through Turbulent Media

Isoplanatic and anisoplanatic imaging conditions



Undistorted image

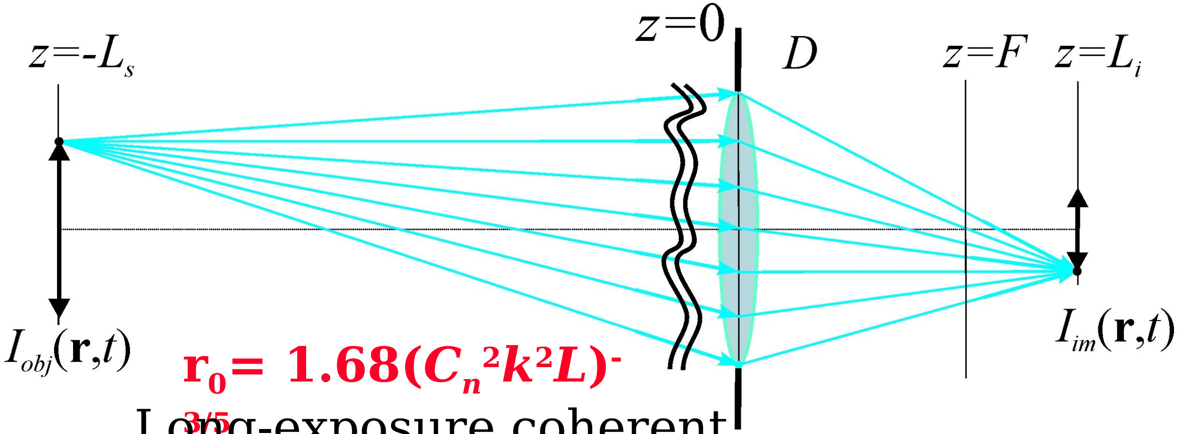
Isoplanatic image: pupil-plane distortion

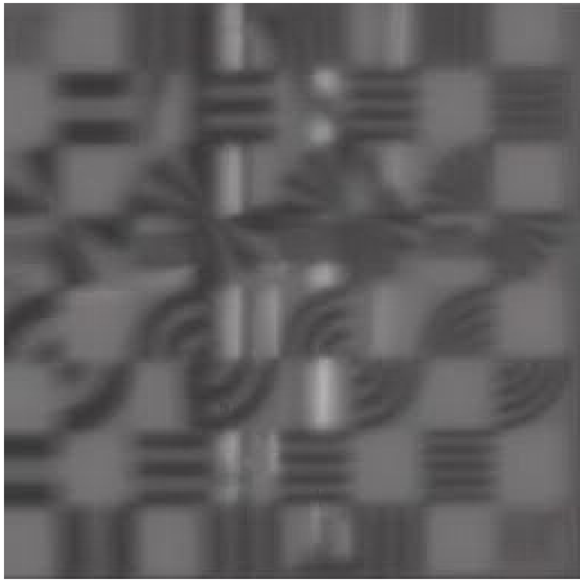
Anisoplanatic image: remote distortion

Photos (a) through (c) correspond to an imaging experiment with a 4x4 array of white light point sources. These were observed through a single layer of heated air created by a base-board heater placed below the telescope at a distance L_ϕ between the object ($z=L_s$) and telescope (z=0) planes: (a) undistorted image; (b) short-exposure distorted image typical of isoplanatic imaging conditions with L_ϕ =0; (c) short-exposure distorted image taken under

Distance L_s =15m, Telescope aperture D=150mm, .

Isoplanatic Imaging: Long-Exposure OTF





$r_0 = 1.68(C_n^2 k^2 L)^{-3/5}$

Long-exposure coherent OTF

$$\langle H(\mathbf{q},t)\rangle_j = P(-\mathbf{q}L_i/k)\langle \exp[i\varphi(-\mathbf{q}L_i/k,t)]\rangle_j = H^d(\mathbf{q})\exp(-\sigma_j^2/2)$$

Long-exposure

$$\langle H_I(\mathbf{q},t)\rangle_j = H_I^d(\mathbf{q})\exp\left[-D_j(qL_I/k)/2\right]$$

$H^d(\boldsymbol{q})$ and $H^d_I(\boldsymbol{q})$ are diffraction-limited transfer functions for coherent, and incoherent imaging system models. The spatial frequency $\boldsymbol{q}$ is normalized by the cut-off f

Optical transfer functions (OTF) for an imagi
with circular aperture of diameter D under i
imaging conditi

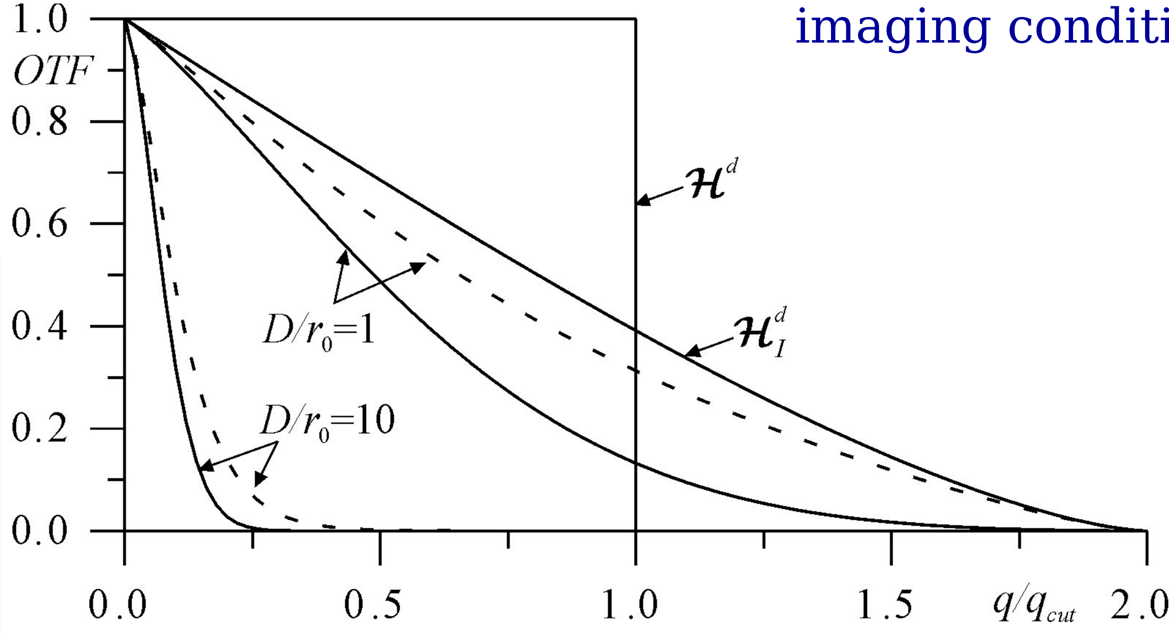
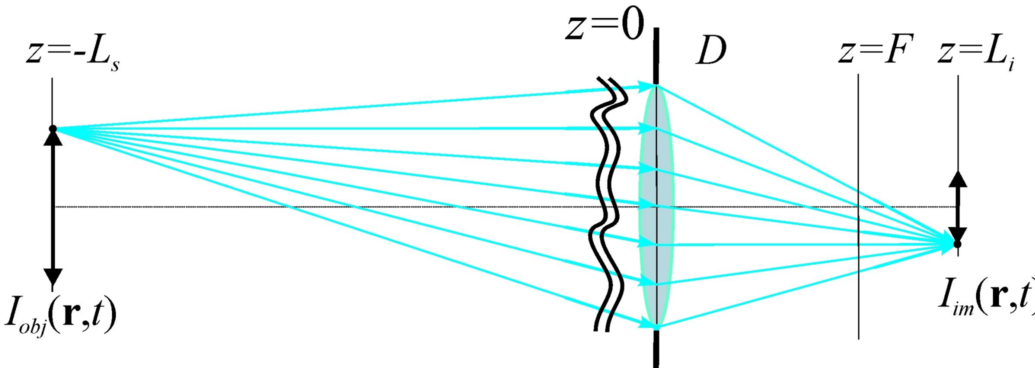
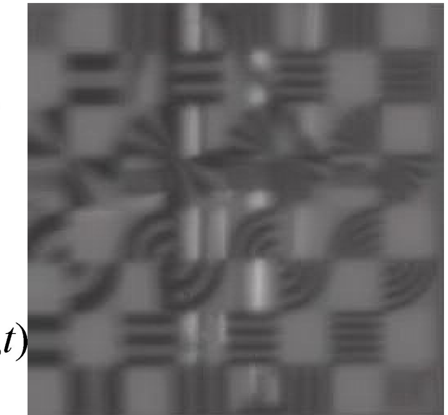
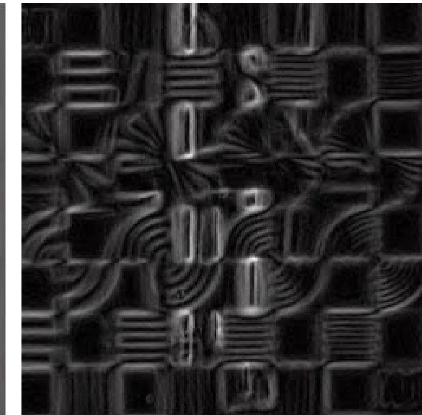
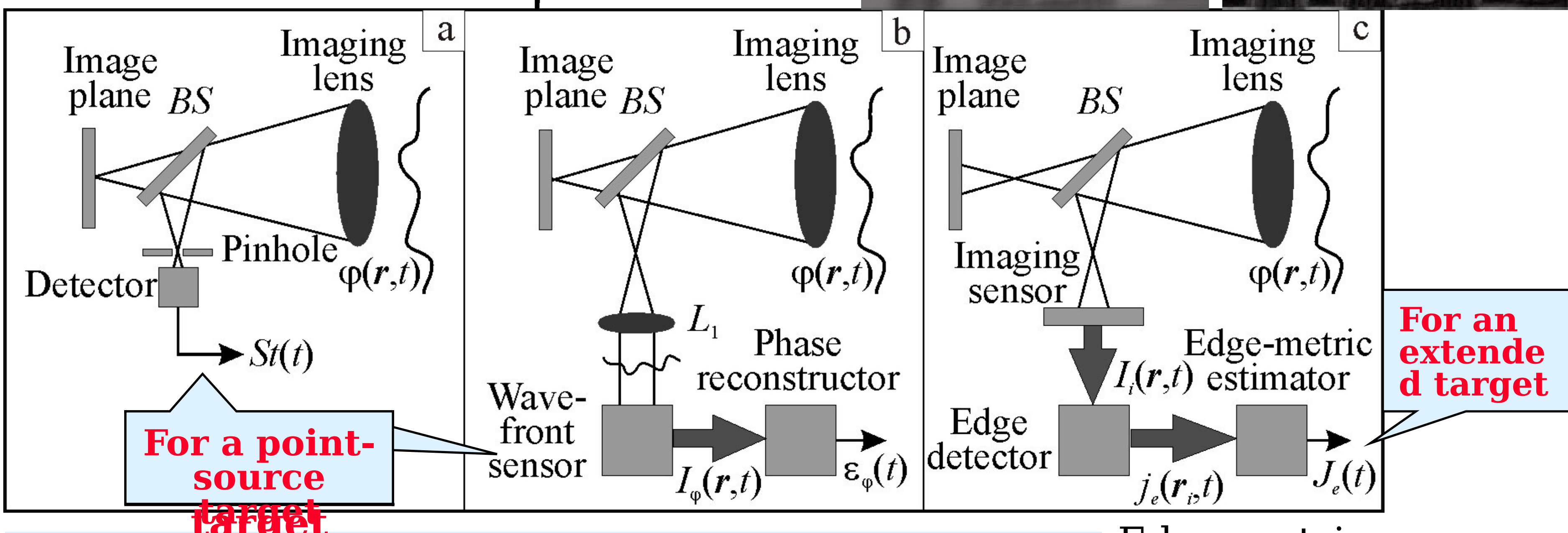


Image Quality Analysis: Image Quality Metrics









Schematics for instantaneous image quality metric measurements:
(a) Strehl ratio $St(t)$; (b) phase-error $\varepsilon_\phi(t)$; (c) edge-metric $J_e(t)$.
The lens L_1 is used to re-image the optical system

Edge-metric

$$J_e = \int |\nabla I(\mathbf{r})|^2 \, d^2\mathbf{r}$$

Sharpnes

$$J_s = \int I^2(\mathbf{r}) \, d^2\mathbf{r}$$

Image Quality Analysis: "Lucky-Frame" Selection

The image quality metric evolution curve

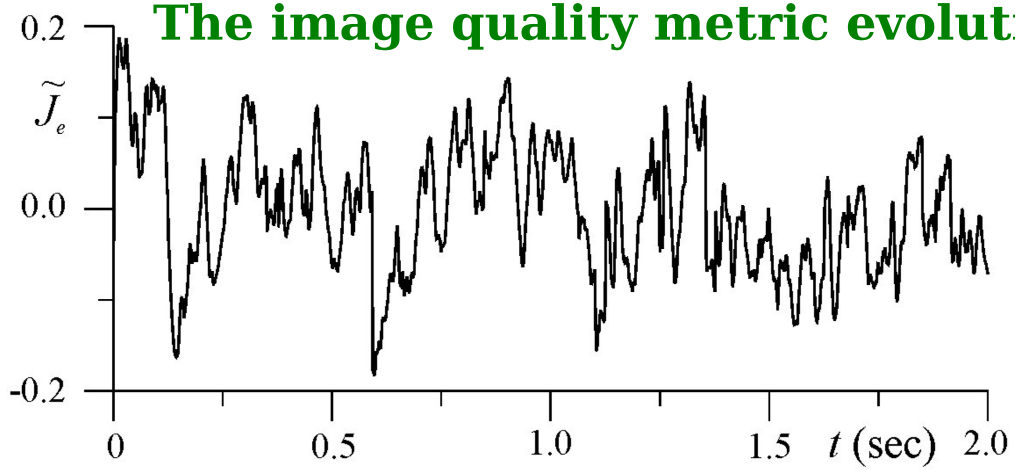
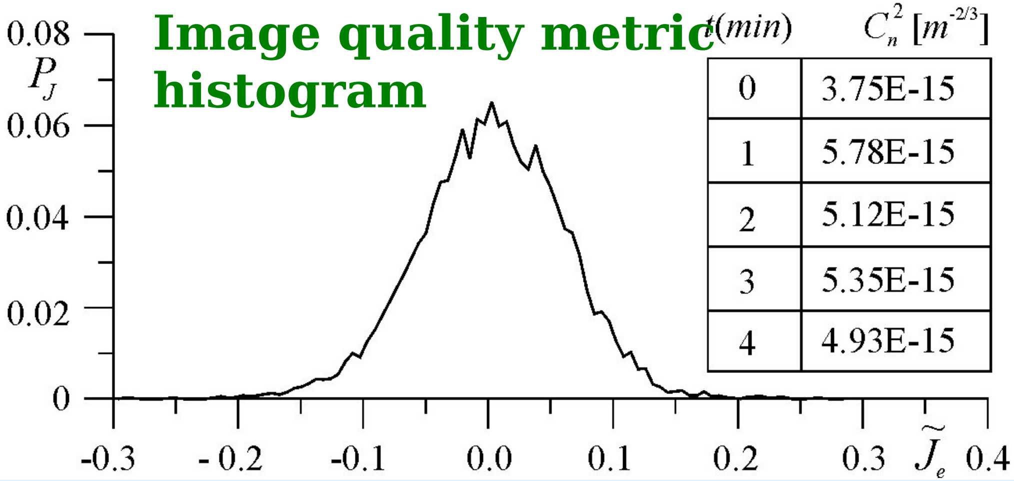
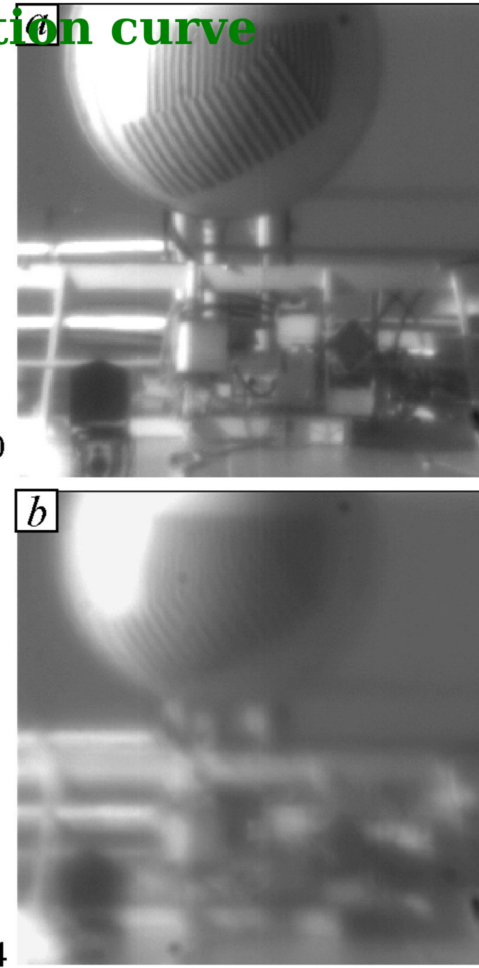


Image quality metric histogram



t(min)	C_n^2 [$m^{-2/3}$]
0	3.75E-15
1	5.78E-15
2	5.12E-15
3	5.35E-15
4	4.93E-15



Best frame

Worse frame

Integration tim
τ=4 msec.
Time interval
between frame
Δt=16 msec

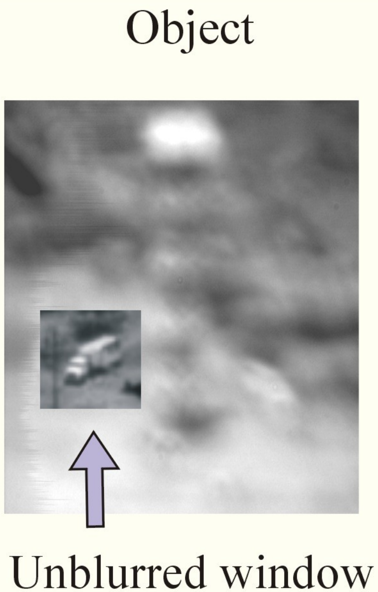
N=1.5*10⁴
images with
8-bit grey-sca
levels and
256x256 pixel
resolution

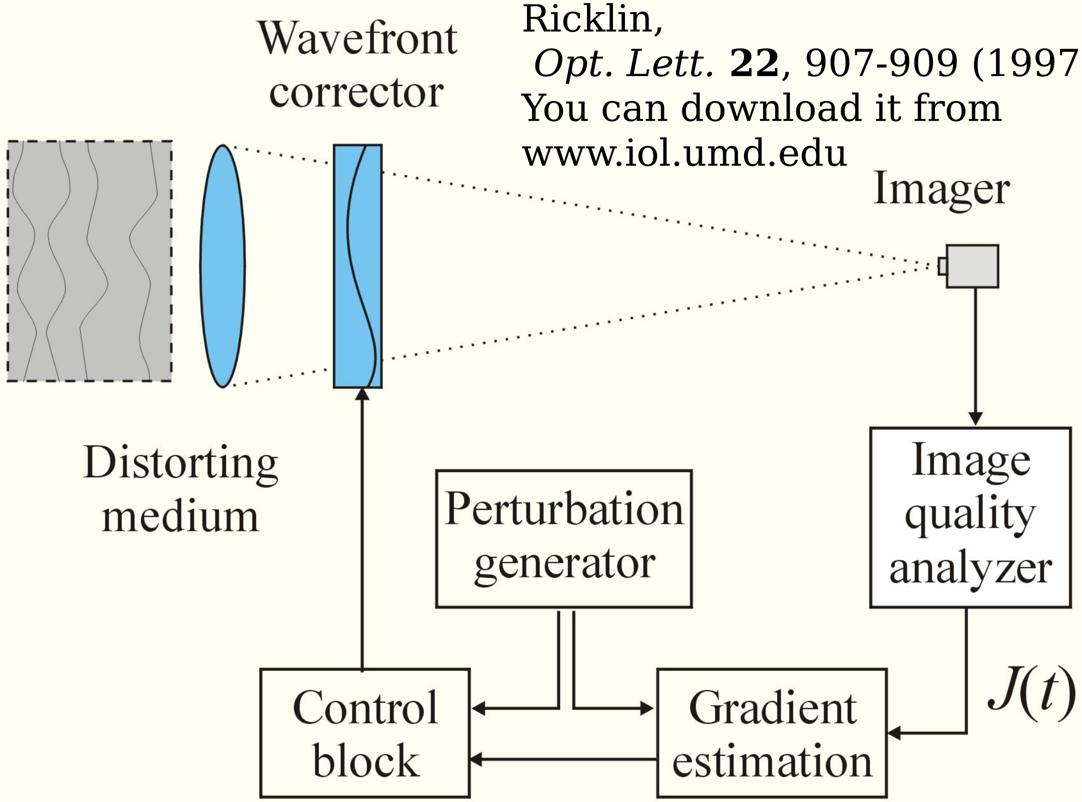
Image quality analysis based on the image quality metric for an atmospheric imaging experiment over a 2.4 km nearly horizontal propagation path. The imaging system included a telescope with aperture *D*=15 cm (F/6) and fast framing CCD camera. The inset table shows changes in C_n^2 during the experiment. The scene imaged contains an RF antenna and various equipment on the top of a water tower. Two resolution charts with black and white bars ar

See M. Vorontsov, SPIE Proc. 5162, (2003

Adaptive Optic Compensation: Image Quality Metric Optimization with Stochastic Parallel Gradient Descent (SPGD) Technique:

M. Vorontsov, G. Carhart and J.C. Ricklin,
Opt. Lett. **22**, 907-909 (1997).
You can download it from
www.iol.umd.edu

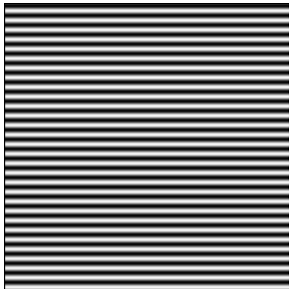


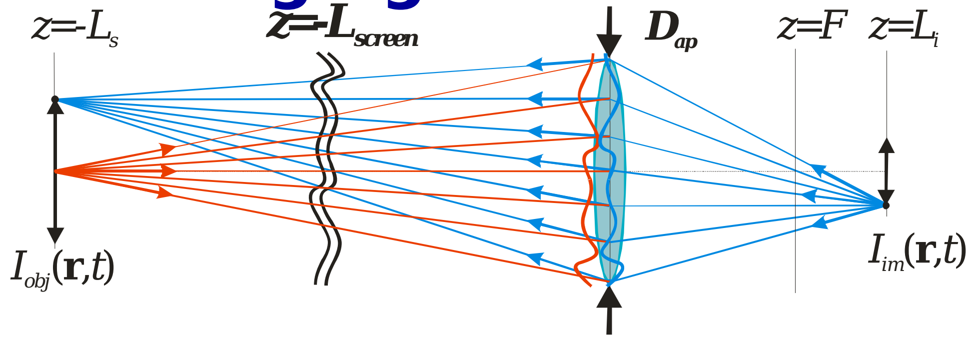


$$u^{(m+1)}(\mathbf{r}) = u^{(m)}(\mathbf{r}) - \mu\delta J(\mathbf{r})\delta u(\mathbf{r})$$

Drawbacks: compensation within a narrow (isoplanatic)

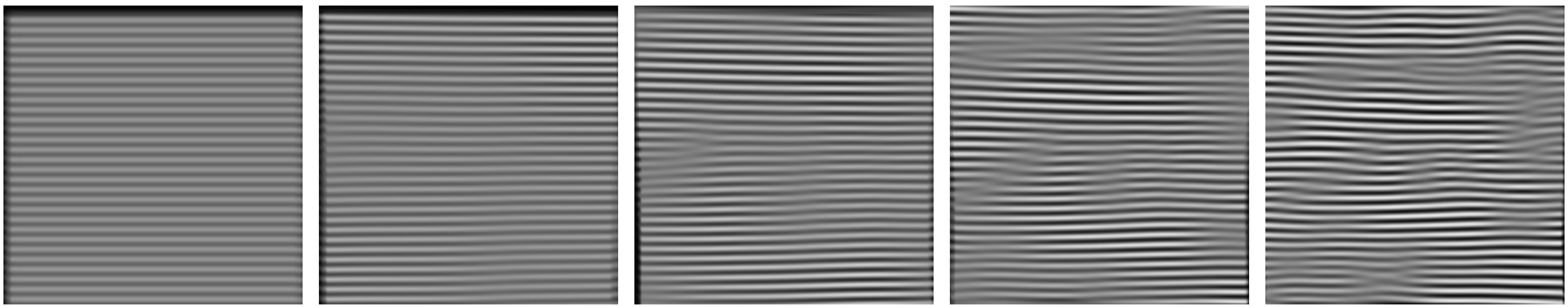
Adaptive Wavefront Distortion Compensation in Anisoplanatic Imaging Conditions



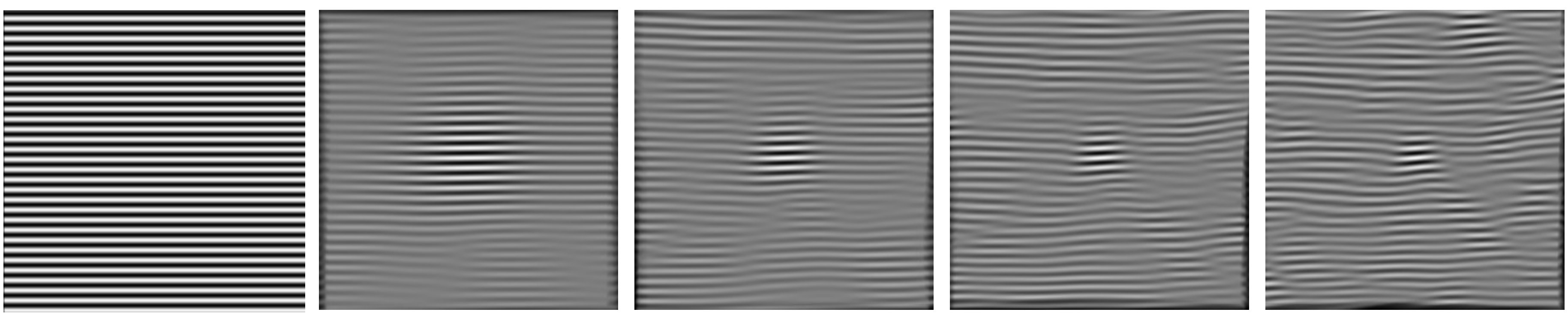


Without adaptive compensation

$L_{screen} = 0$ | $L_{screen} = 0.1L_s$ | $L_{screen} = 0.2L_s$ | $L_{screen} = 0.3L_s$ | $L_{screen} = 0.4L_s$

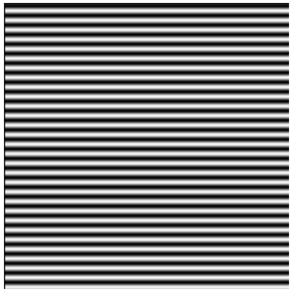


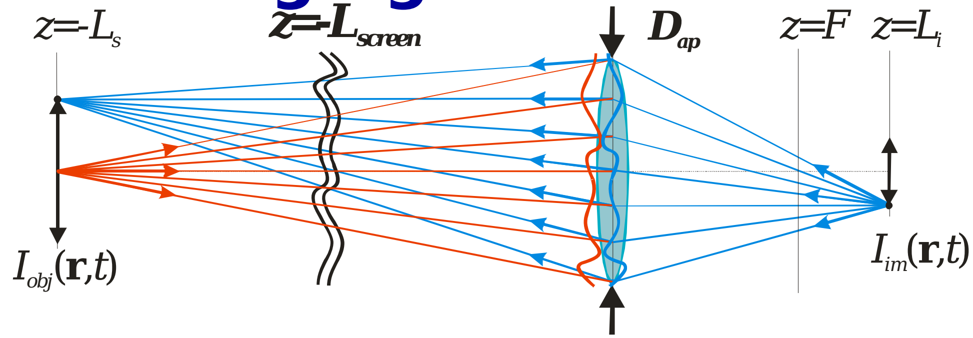
With adaptive compensation based on conjugation of phase for a single target point



V. Dudorov and M. Vorontsov (to be publi

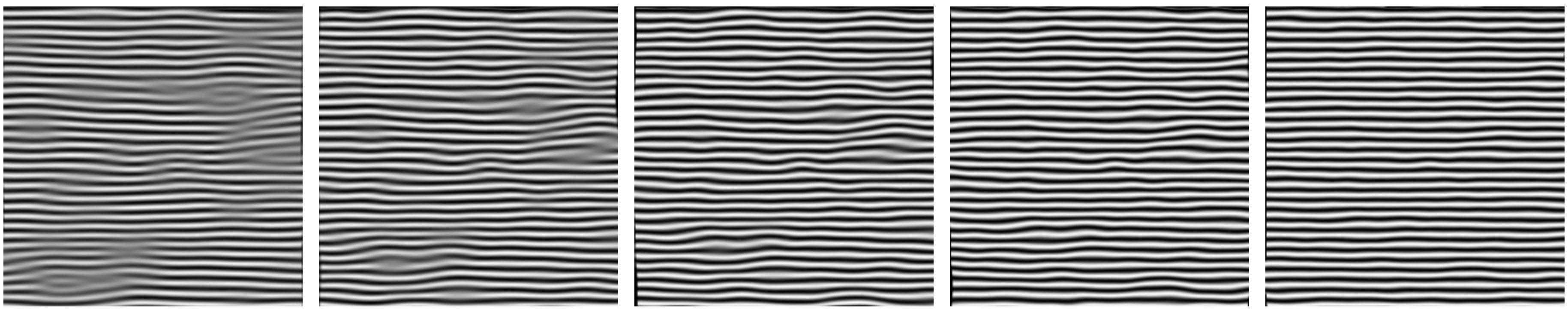
Adaptive Wavefront Distortion Compensation in Anisoplanatic Imaging Conditions



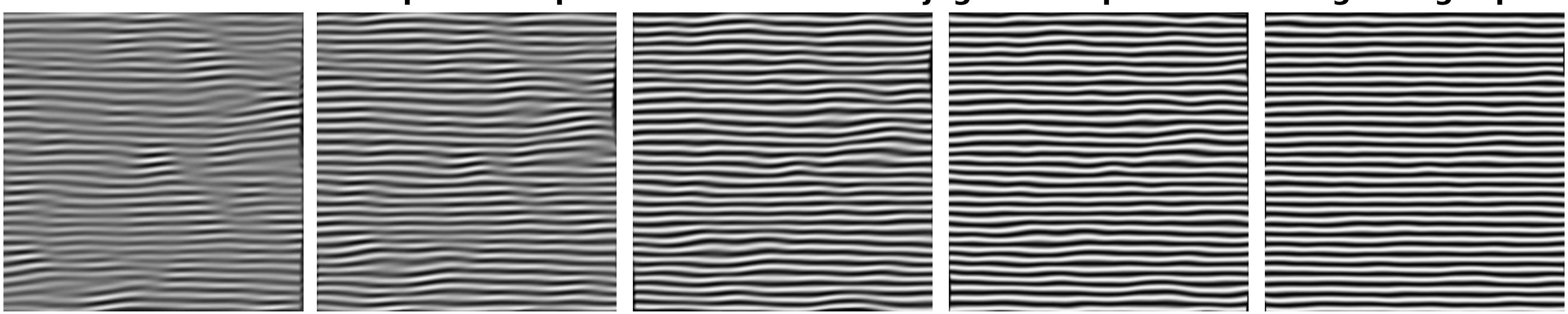


Without adaptive compensation

$L_{screen}=0.5L_s$ $L_{screen}=0.6L_s$ $L_{screen}=0.7L_s$ $L_{screen}=0.8L_s$ $L_{screen}=0.9L_s$



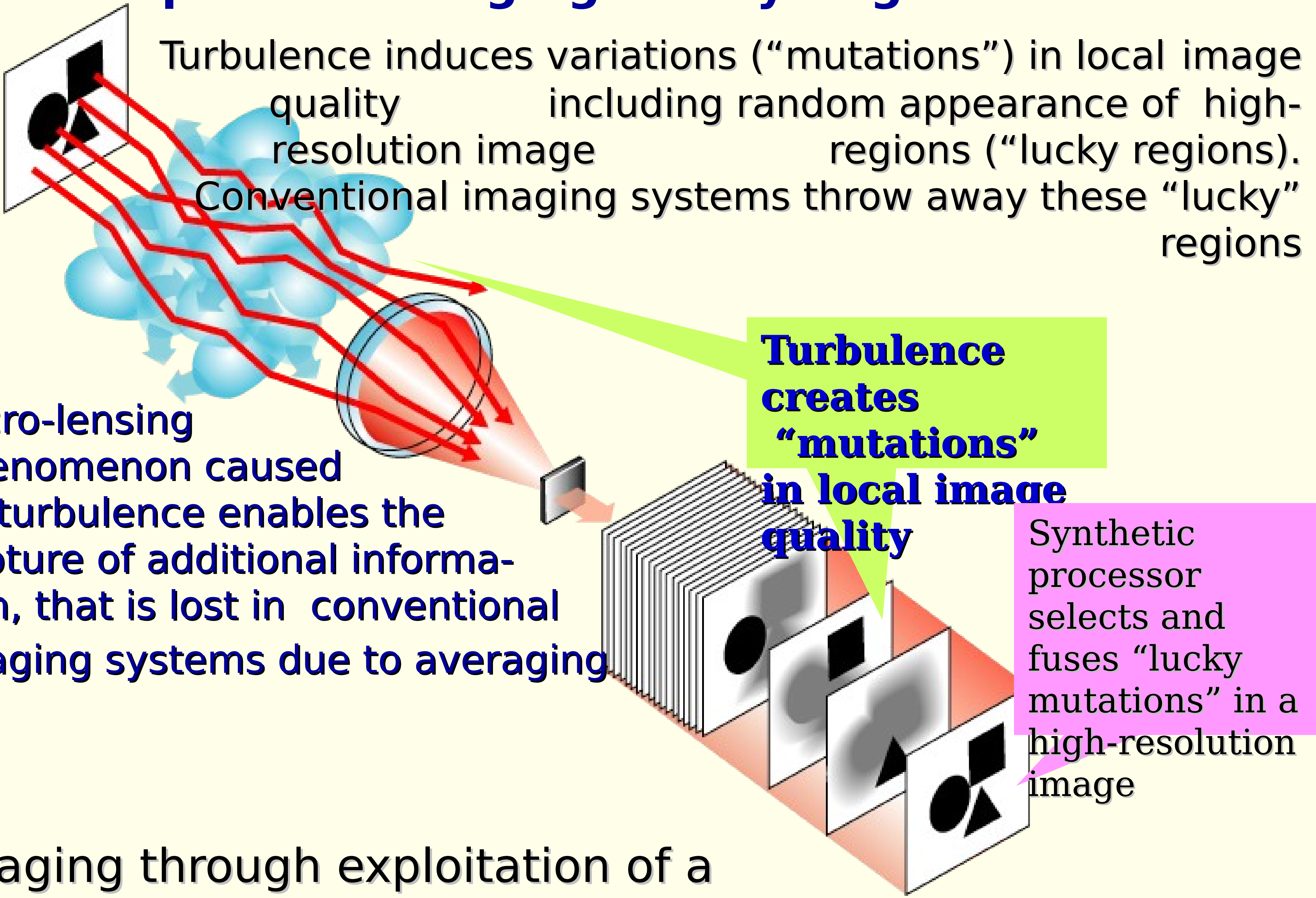
With adaptive compensation based on conjugation of phase for a single target point



V. Dudorov and M. Vorontsov (to be publi

Anisoplanatic Imaging: Lucky Region Fusion Techn

Turbulence induces variations ("mutations") in local image quality including random appearance of high-resolution image regions ("lucky regions). Conventional imaging systems throw away these "lucky" regions

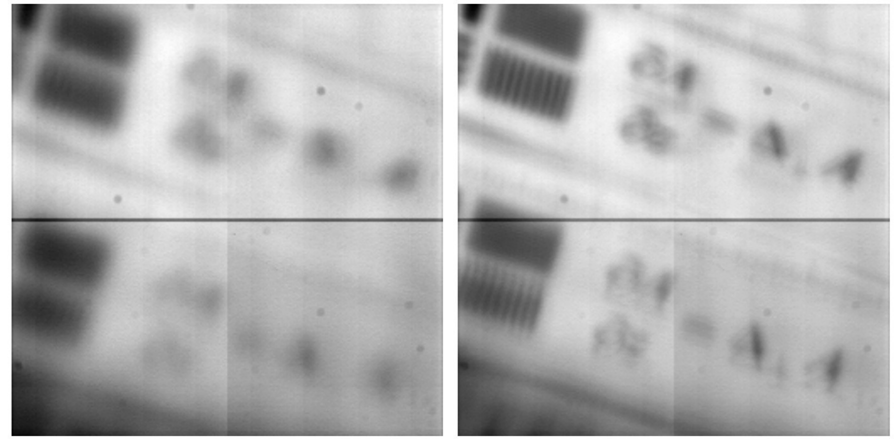


Micro-lensing phenomenon caused by turbulence enables the capture of additional informa-tion, that is lost in conventional imaging systems due to averaging

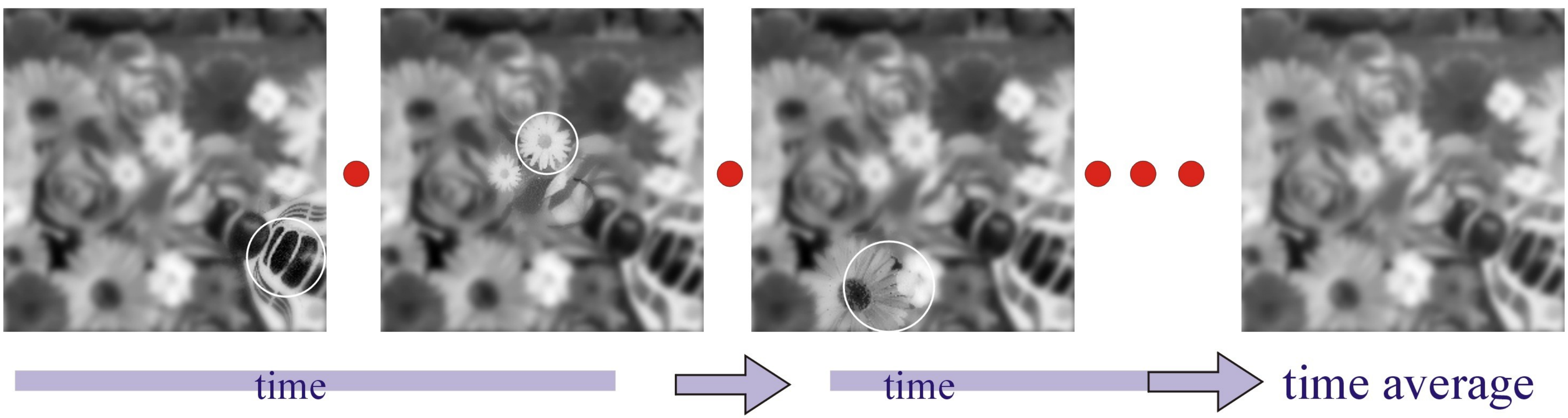
Imaging through exploitation of a random media focusing effect by "lucky" regions fusion

Anisoplanatic Imaging Through Turbulent Media

Path length 6500 m Camera (EG&G Reticon)
80 frames/sec. (Courtesy: A. Kohnle)

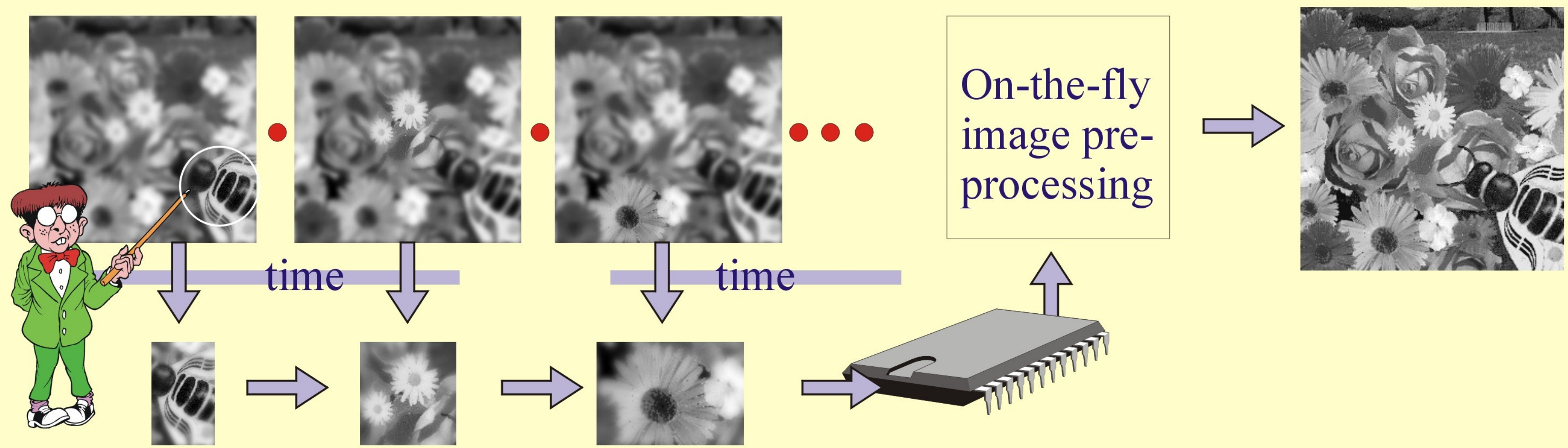


Path length 250 m 60 frames/sec.



Approaches: Adaptive Optics, Frame selection, Post-processing

Local Information Fusion from a Set of Short-Exposure Images: Synthetic Imaging



Global and local image quality analysis

Image quality metric

$$J_d(t) = \gamma \int |\nabla_\perp^2 I(\mathbf{r},t)|^2 d^2\mathbf{r}$$

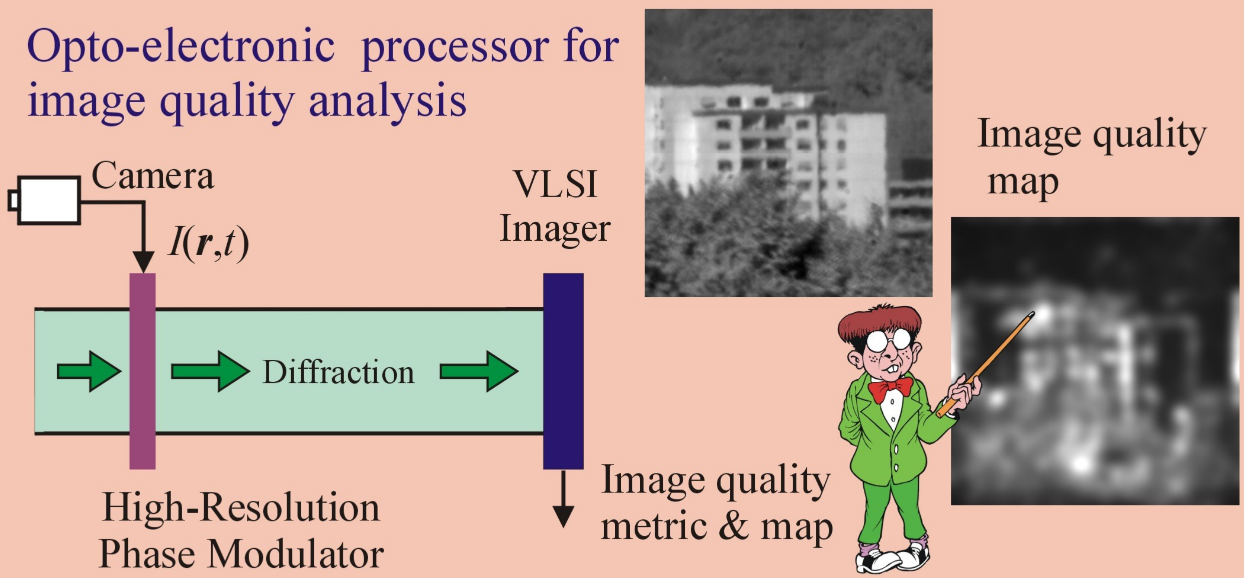
(Muller, Buffington, 1974)

Image quality map

$$J(\mathbf{r},t) = \gamma \int |\rho(\mathbf{r}'-\mathbf{r}) \nabla_\perp^2 I(\mathbf{r}',t)|^2 d^2\mathbf{r}'$$

(Vorontsov, 1999)

Opto-electronic processor for image quality analysis



$$I_d(\mathbf{r},t) = |A(\mathbf{r},t,z=L)|^2$$

$$I_d(\mathbf{r},t) \cong I_0 + I_0 \frac{L}{k} \alpha \nabla_\perp^2 I(\mathbf{r},t)$$

Local Image Quality Analysis: Image Quality Ma

$$J(\mathbf{r}) = \int |\nabla I(\mathbf{r}')|^2 \rho(\mathbf{r}' - \mathbf{r}, a) d^2\mathbf{r}'$$

$\rho(\boldsymbol{r}, a) = \exp[-(x^2 + y^2)/a^2]$, a is the kern

The image quality map characterizes the contribution of high spatial spectral components (edges) in an image frame local area of radius a with a center point $\boldsymbol{r}$

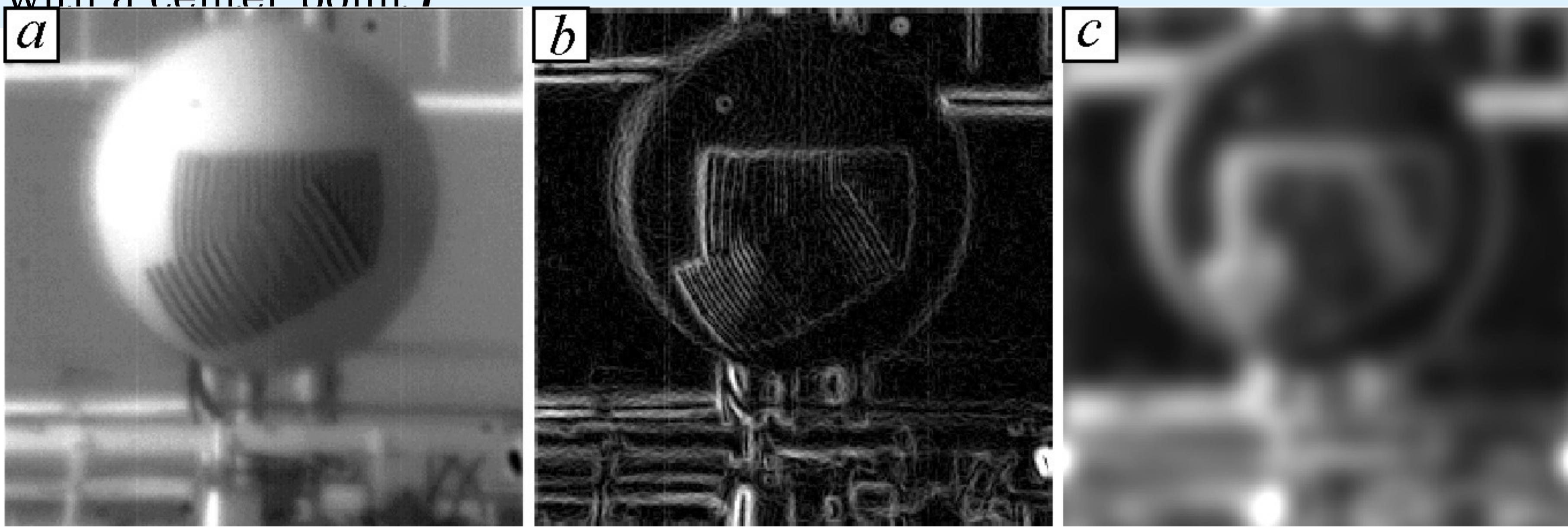


Image quality analysis in anisoplanatic conditions: single short-exposure im atmospheric turbulence (a); edge-image calculated using Sobol digital gra approximation (b); and image quality map for Gaussian kernel with radius a is the image area size), $D/r_0=6$

1. M. A. Vorontsov, *Wavefront Control in Optics*, Oxford University Press, (to

Image Processing Based on Nonlinear Diffusion PDE with Anisotropic Gain: Cost-Functional Minimization

$$E(I_s) = \tfrac{1}{2}\int_{\Omega} \{\alpha\, |\nabla I_s(\mathbf{r})|^2 + \beta J(\mathbf{r})[I_s(\mathbf{r}) - I(\mathbf{r})]^2\}\, d^2\mathbf{r}$$

Synthetic image — Input image

Image processing is considered as a process of minimizing the cost-functional *E*. The function $J(r)$ acts as a penalty for infidelity to the input image. Due to the anisotropy of $J(r)$ the penalty is higher in t vicinity of image edges. During the cost functional minimization pro the difference is forced to be small only in the vicinity of the edge, providing selectivity in image smoothness.

Synthetic imaging equation

$$\frac{\partial I_s(\mathbf{r},t)}{\partial t} = \alpha \nabla^2 I_s(\mathbf{r},t) - \beta J(\mathbf{r})[I_s(\mathbf{r},t) - I(\mathbf{r},t)]$$

Image quality map — Synthetic image — Input image

Vorontsov, M. A., G. W. Carhart, *JOSA A* Vol. 18, No 6, 1312,

Image Synthesis Based on PDE Process: Synthetic I

Vorontsov, JOSA A, 1999, 1623

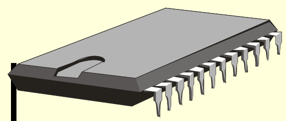
Object

Optical system

Sensor

$I(\mathbf{r},t)$

Input image flow

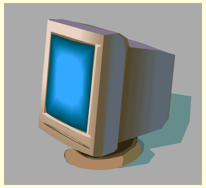


Edge-detector $|\nabla I(\mathbf{r},t)|$

Edge-map $J(\mathbf{r}) = \int \rho(\mathbf{r}' - \mathbf{r}, a)\,|\nabla I(\mathbf{r}')|\,d^2\mathbf{r}'$

$J^s(\mathbf{r}) = \int \rho(\mathbf{r}'\mathbf{r})\,|\nabla I^s(\mathbf{r}')|\,d^2\mathbf{r}$

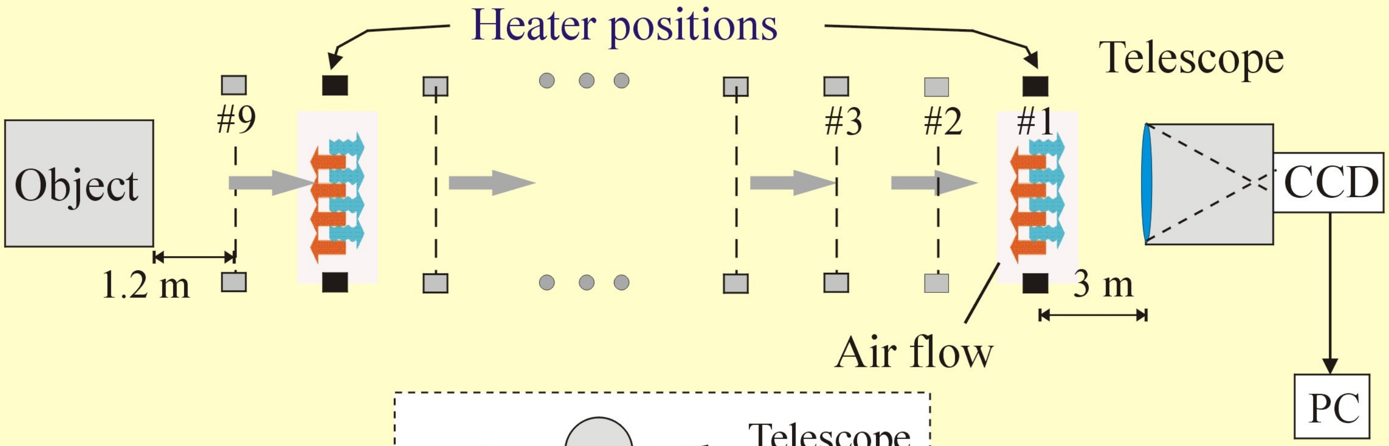
$$\delta(\boldsymbol{r},t) = \begin{cases} J(\boldsymbol{r},t_n) - J^s(\boldsymbol{r},t) & \text{for } J(\boldsymbol{r},t_n) > J^s(\boldsymbol{r},t) \\ 0 & \text{otherwise} \end{cases}.$$



PDE process $$\tau \frac{\partial I^s(\boldsymbol{r},t)}{\partial t} = -K\,\delta(\boldsymbol{r},t)[I^s(\boldsymbol{r},t) - I(\boldsymbol{r},t_n)]$$

$I^s(\mathbf{r},t)$

Anisoplanatic Imaging Through Turbulent Media: Experimental Setup



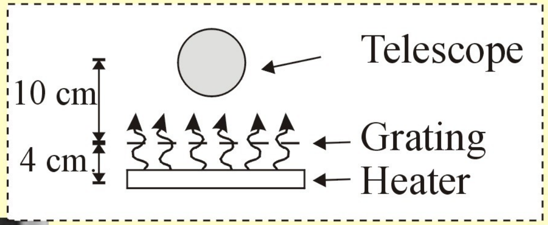
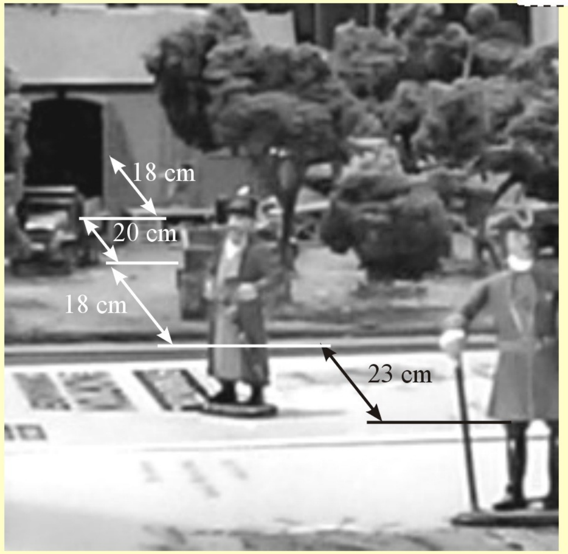


Image scene geometry



System parameters

Telescope diameter
D= 90 mm

Imaging system
view angle 7.2 mrad.

DALSA digital
camera - 100 fr/sec.
256x256 resolution
8 bit

Propagation
distance L= 14 m

Image in the absence of turbulence

Synthetic Imaging Examples

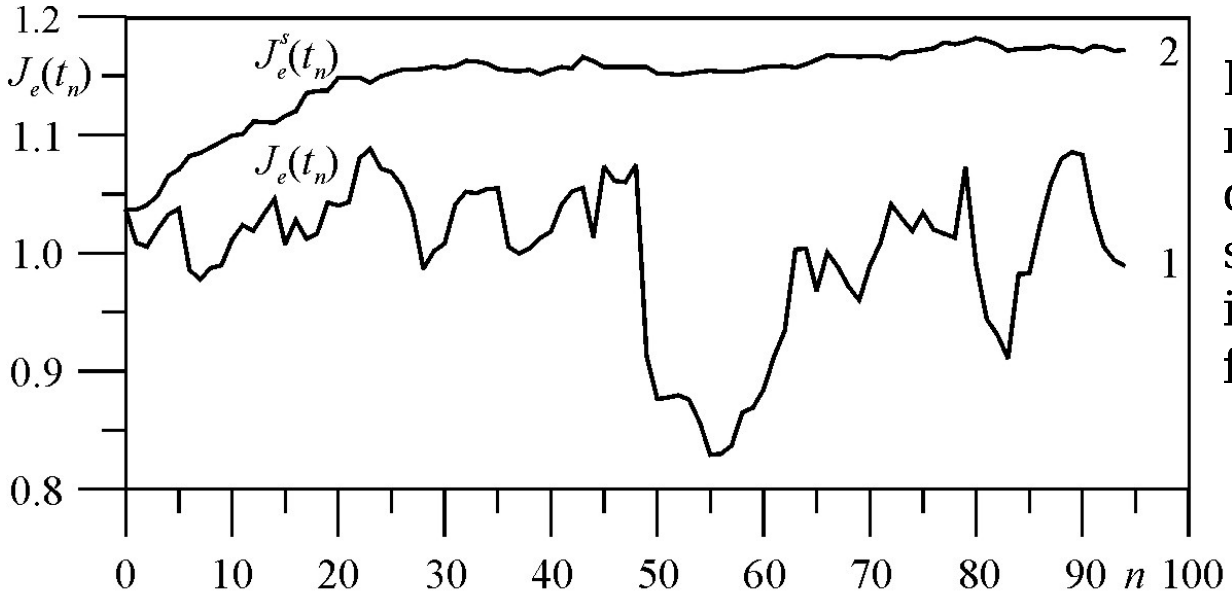
Long-exposure image

Synthetic image

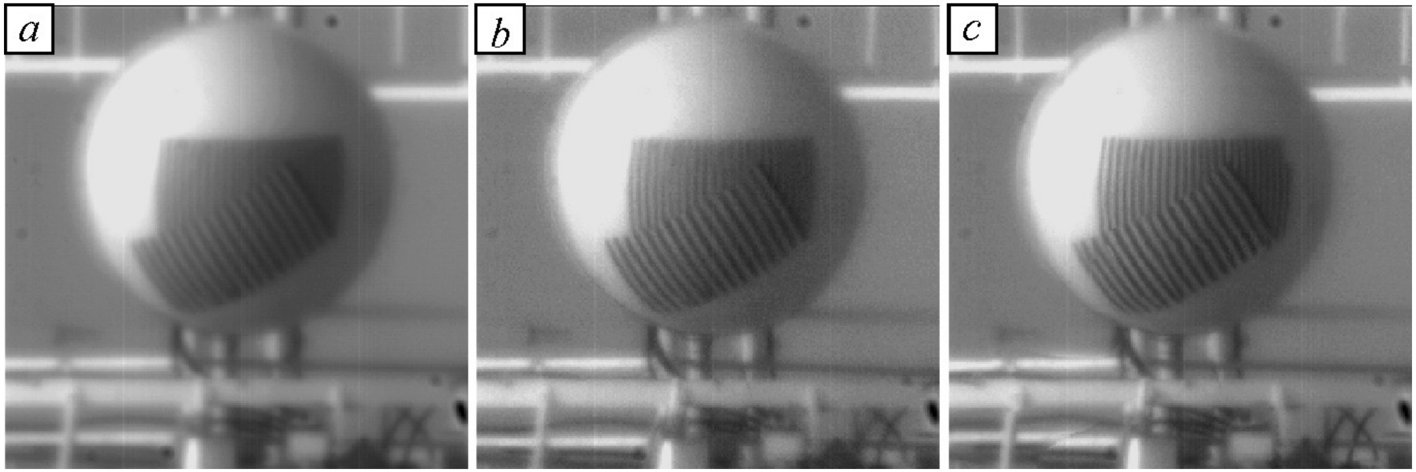
Path length
15 m,
500 fr. Lab.
generated
turbulence
(2 heaters)

Path length
6500 m,
100 frames

Synthetic Imaging: Atmospheric Experimen

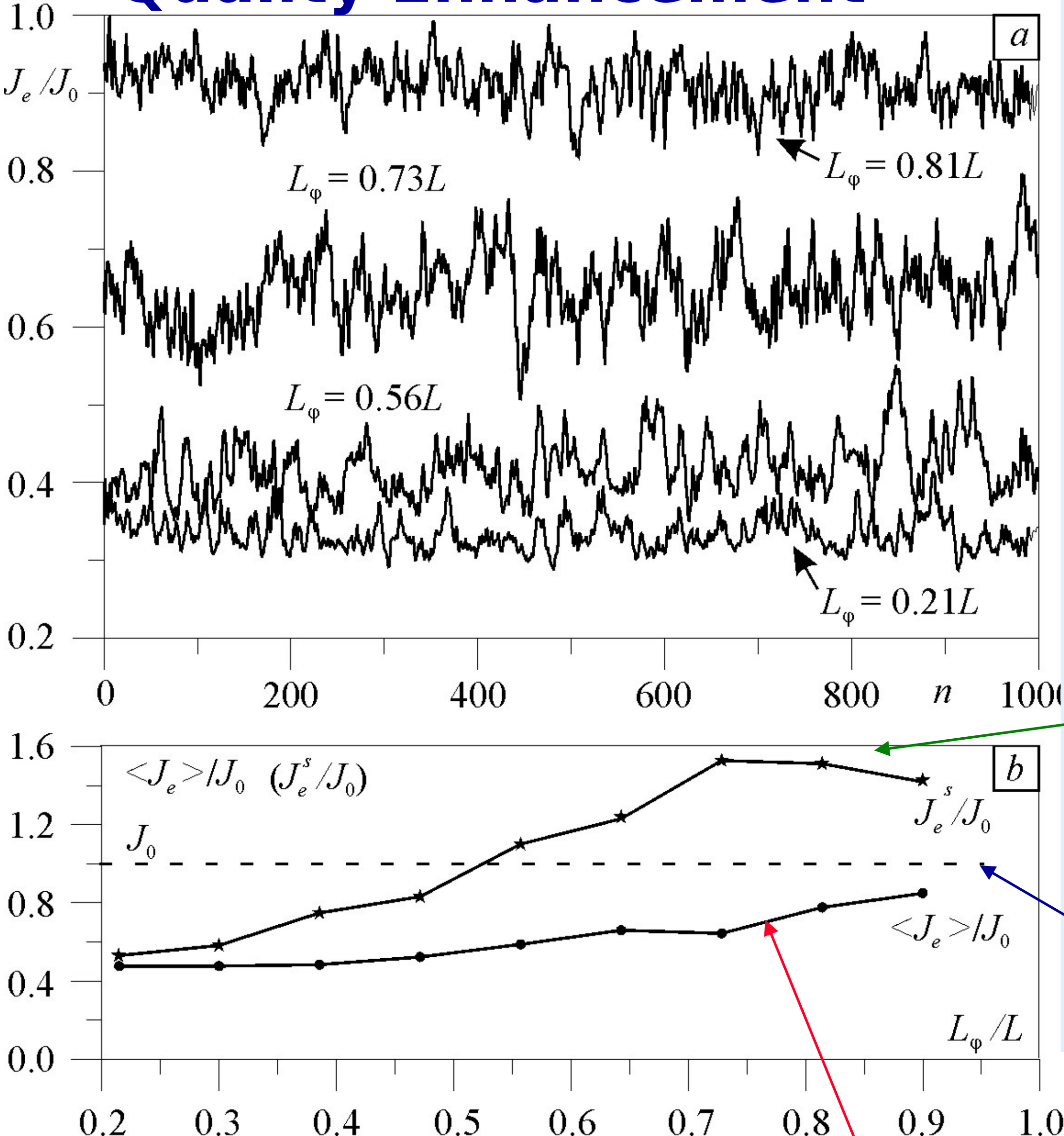


Evolution curves
normalized imag
quality metrics
short-exposure
images (1), and
for synthetic ima



Local information fusion from a set of N=100 short-exposure atmospheric a
using synthetic imaging technique: (a) frame-averaged image, (b) "lucky" fr
(c) synthetic image frame

Anisoplanatic Imaging: Turbulence-Induced Image Quality Enhancement



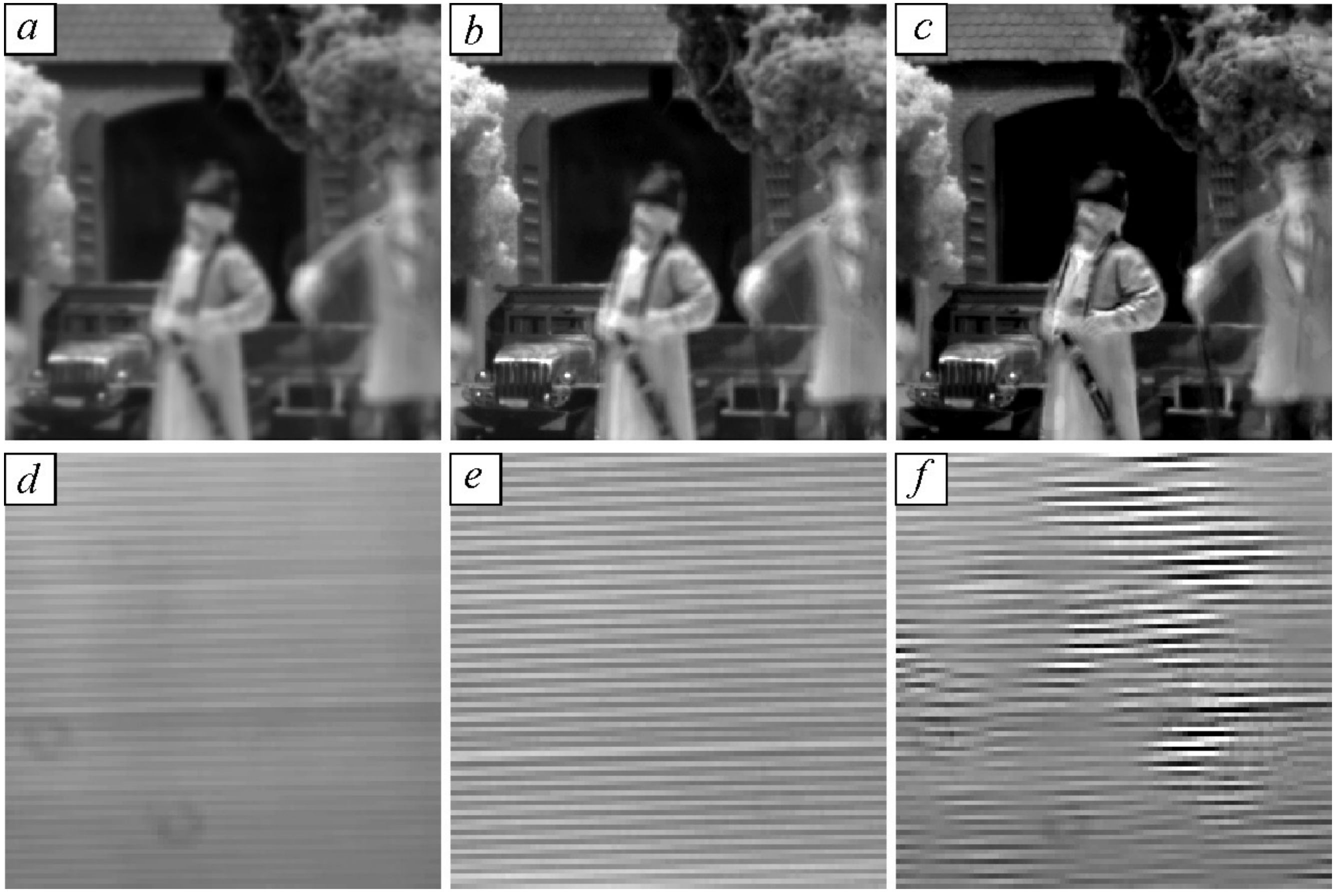
Anisoplanatic imaging experiment with a single laboratory-generated phase distorting layer placed a distance L_ϕ from the imaging telescope: (a) image quality metric evolution curve, (b) frame-averaged $<J_e>$ and synthetic $<J_e^s>$ image quality metrics as a function of L_ϕ. Synthetic image calculations are based on a set of N=1000 short-exposure images taken at a rate of 200 f/s. The image quality metric values are normalized by the undistorted image quality metric J_0 shown by the dashed horizontal curve in (b).

Super-resolution

Diffraction limited

Turbulence degraded

Turbulence-Induced Image Quality Enhancement: Super-Resolution



Imaging a scene wit
several extended ob
placed at different
distances. The imag
telescope is focused
the truck.

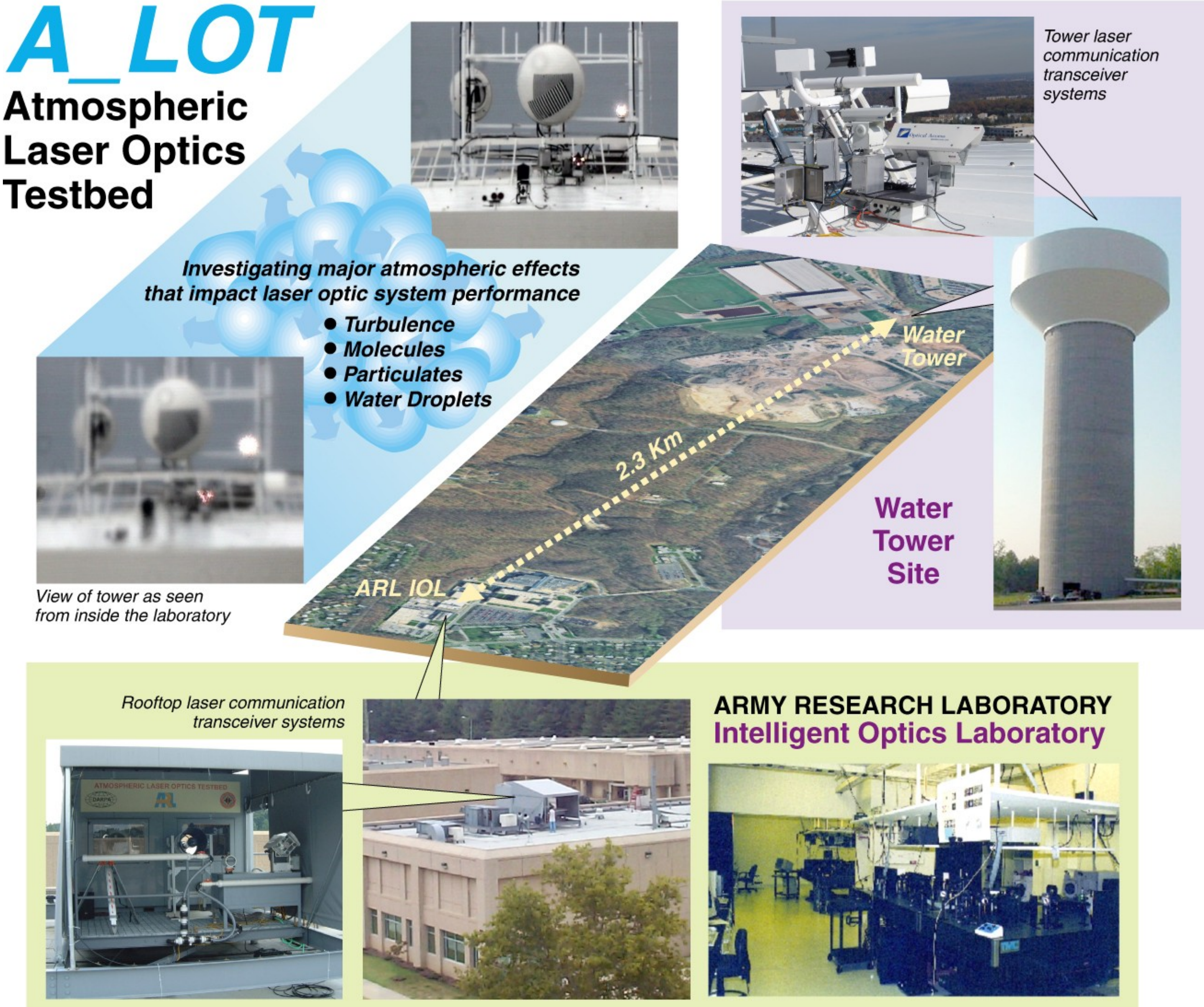
Imaging a sine resol
chart

Averaged images

Undistorted images

Synthetic images

Image enhancement obtained with the synthetic imaging technique for a si
generated turbulent layer located at $L_\phi = 0.7L$.


A_LOT
Atmospheric Laser Optics Testbed
Investigating major atmospheric effects that impact laser optic system performance
• Turbulence
• Molecules
• Particulates
• Water Droplets
View of tower as seen from inside the laboratory
Tower laser communication transceiver systems
Water Tower
2.3 Km
ARL IOL
Water Tower Site
Rooftop laser communication transceiver systems
ATMOSPHERIC LASER OPTICS TESTBED
DARPA
ARL
ARMY RESEARCH LABORATORY
Intelligent Optics Laboratory